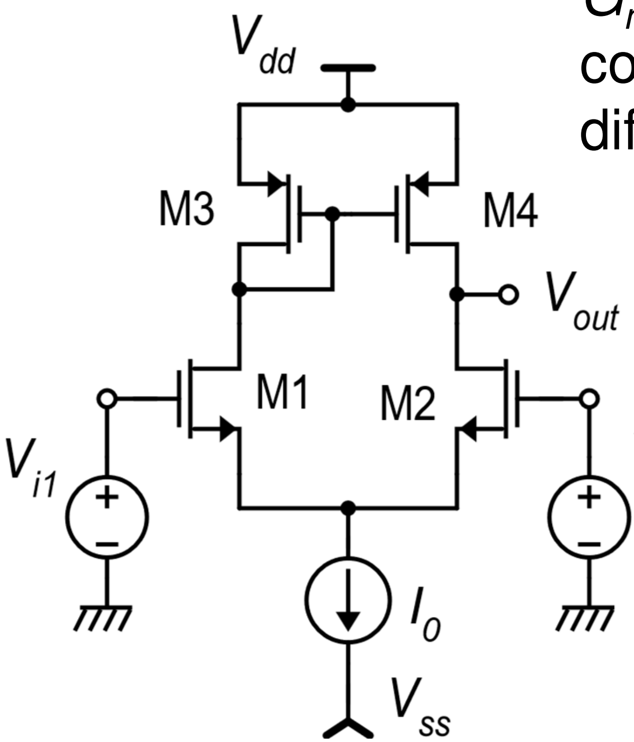
Increasing the gain of the simple differential amplifier with mirror load

$$R_{out} = r_{d2} \,//\, r_{d4}$$

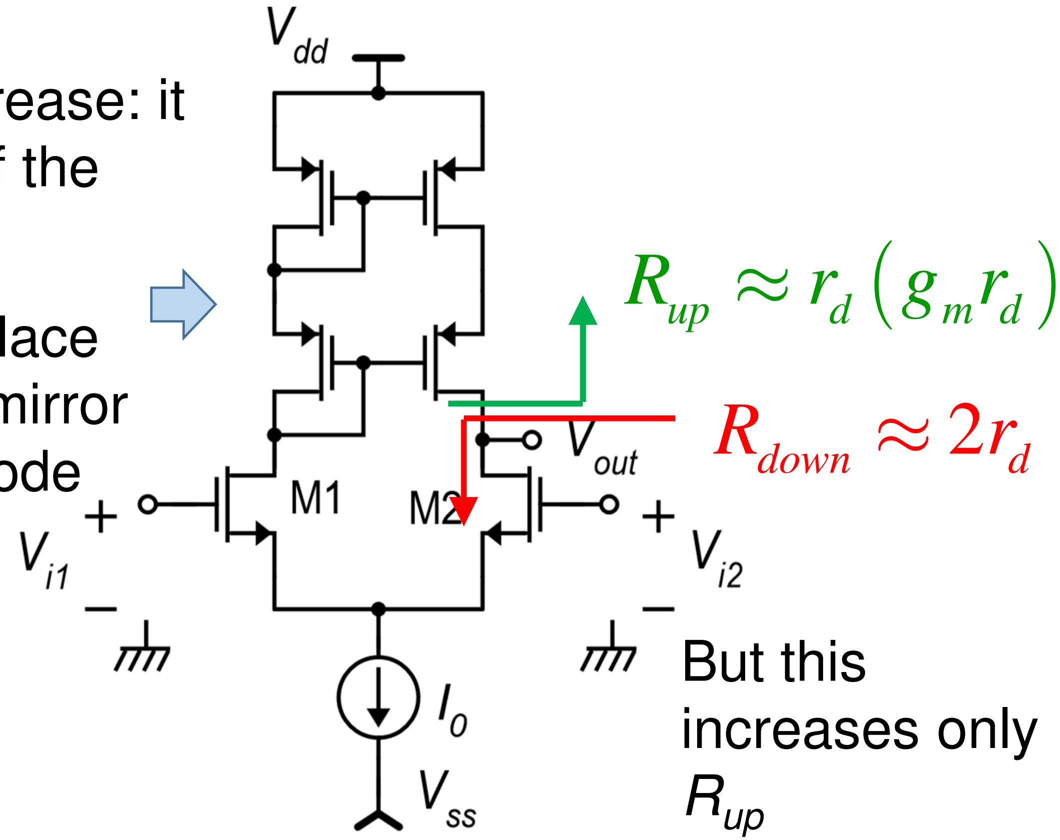
$$A_d = G_m R_{out}$$

We need to increase the output resistance

G_m is difficult to increase: it coincides with g_m of the differential pair

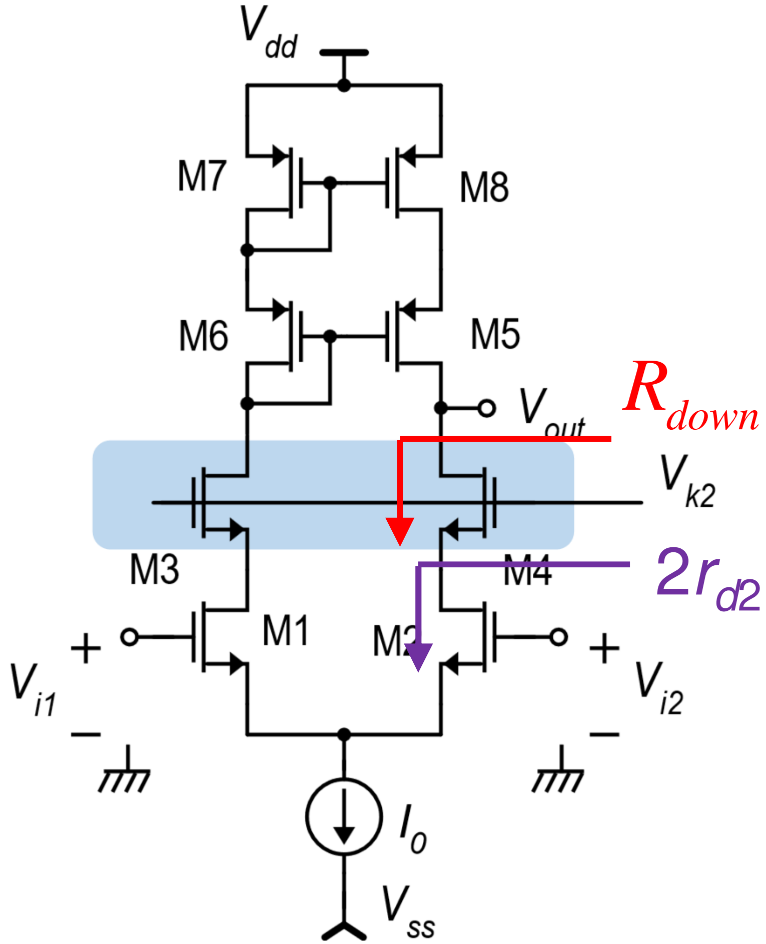


We can replace the simple mirror with a cascode mirror



But this increases only R_{up}

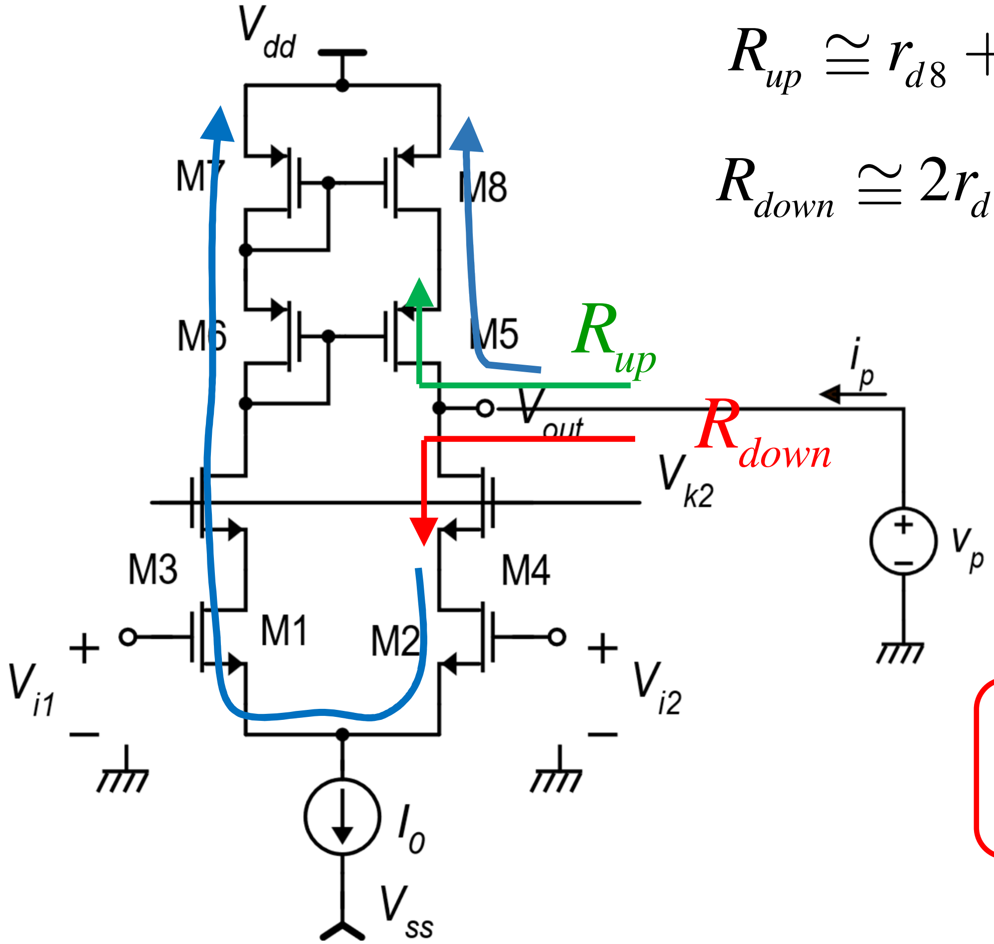
Cascode differential amplifier



$$R_{down} \cong 2r_{d2} + r_{d4}\left(1 + g_{m4} 2r_{d2}\right)$$

We add a differential common gate stage (M3,M4) to the differential pair: forming a differential cascode stage

Cascode differential amplifier: R_{out}



$$R_{up} \cong r_{d8} + r_{d5}\left(1 + r_{d8} g_{m5}\right) \cong r_{d5}\left(r_{d8} g_{m5}\right)$$

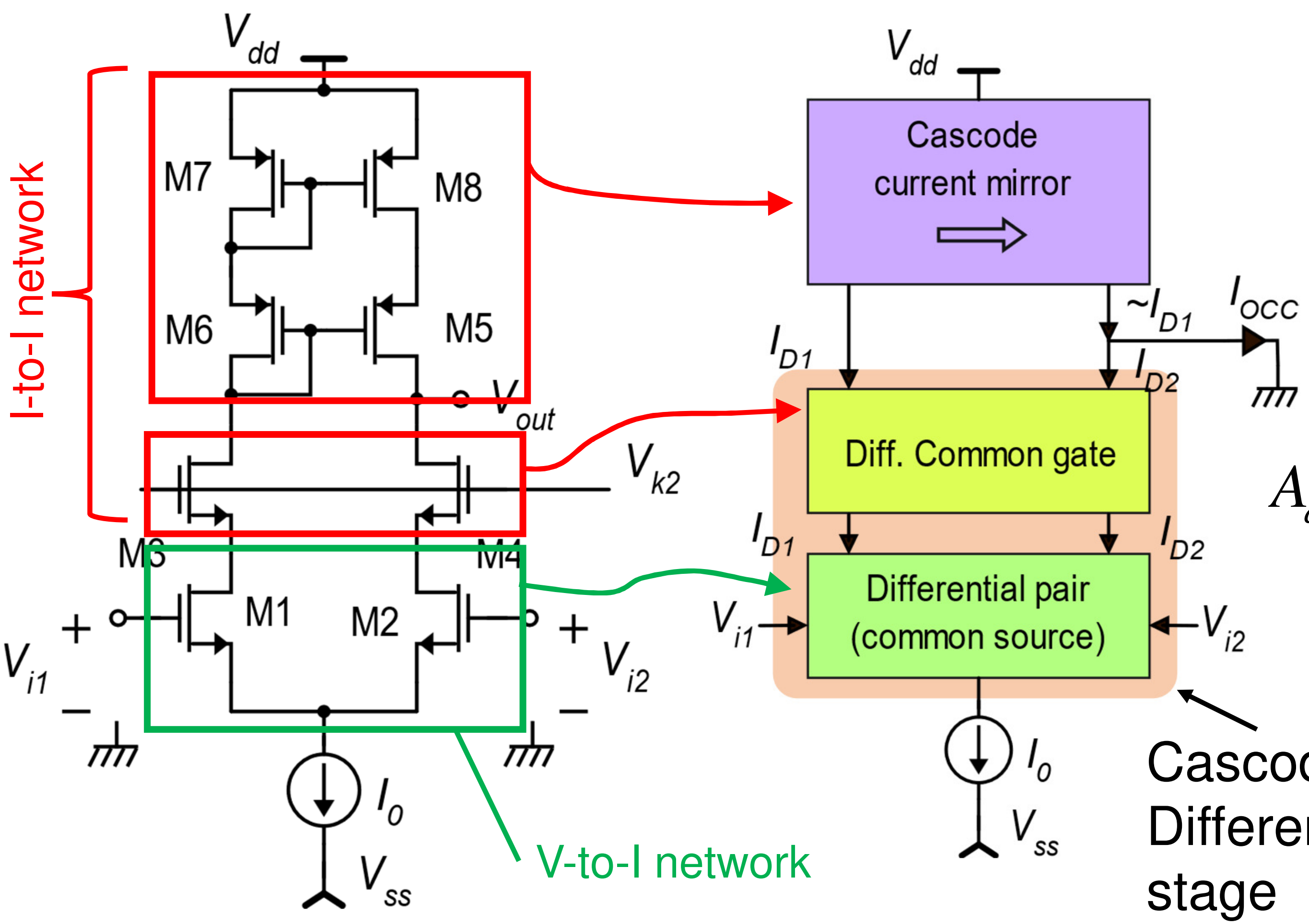
$$R_{down} \cong 2r_{d2} + r_{d4}\left(1 + g_{m4} \cdot 2r_{d2}\right) \cong 2r_{d4}\left(r_{d2} g_{m4}\right)$$

$$i_p = \frac{v_p}{R_{up}} + 2\frac{v_p}{R_{down}}$$

$$R_{out} = R_{up} // \left(\frac{R_{down}}{2}\right)$$

$$R_{out} \cong r_{d5}\left(r_{d8} g_{m5}\right) // r_{d4}\left(r_{d2} g_{m4}\right)$$

Cascode differential amplifier



$$I_{OCC} \cong I_{D1} - I_{D2} \cong g_{m1} v_d$$

$$I_{OCC} = G_m v_d$$

$$G_m = g_{m1}$$

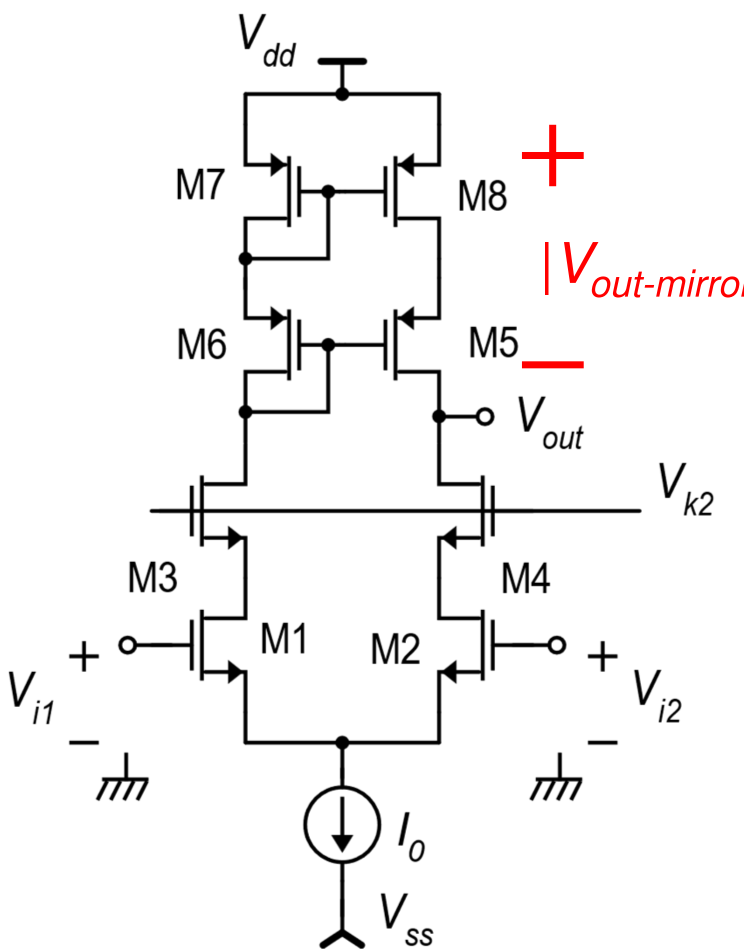
$$A_d = G_m R_{out}$$

$$A_d \cong g_{m1}\left[\left(r_{d2} g_{m4} r_{d4}\right) // \left(r_{d8} g_{m5} r_{d5}\right)\right]$$

If all devices have the same r_d and g_m:

$$A_d \cong \frac{\left(g_m r_d\right)^2}{2}$$

CMOS cascode amplifier: output range



Upper limit

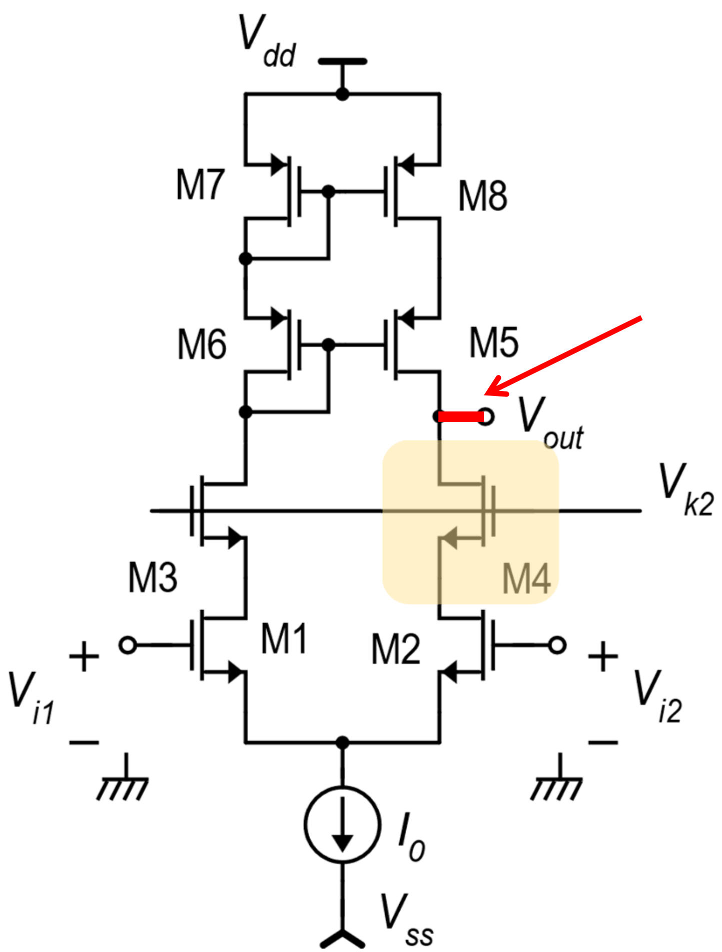
$$\left|V_{out-mirror}\right| = V_{dd} - V_{out} \geq V_{MIN-cascode}$$

$$V_{dd} - V_{MIN-cascode} \geq V_{out}$$

$$\max\left(V_{out}\right) = V_{dd} - V_{MIN-cascode}$$

As V_{out} gets higher than max(V_{out}), R_{up} decreases making the gain decrease

CMOS cascode amplifier: output range



Lower limit

$$V_{DS4} = V_{out} - V_{S4} \geq V_{DSAT4}$$

$$V_{S4} = V_{k2} - V_{GS4}$$

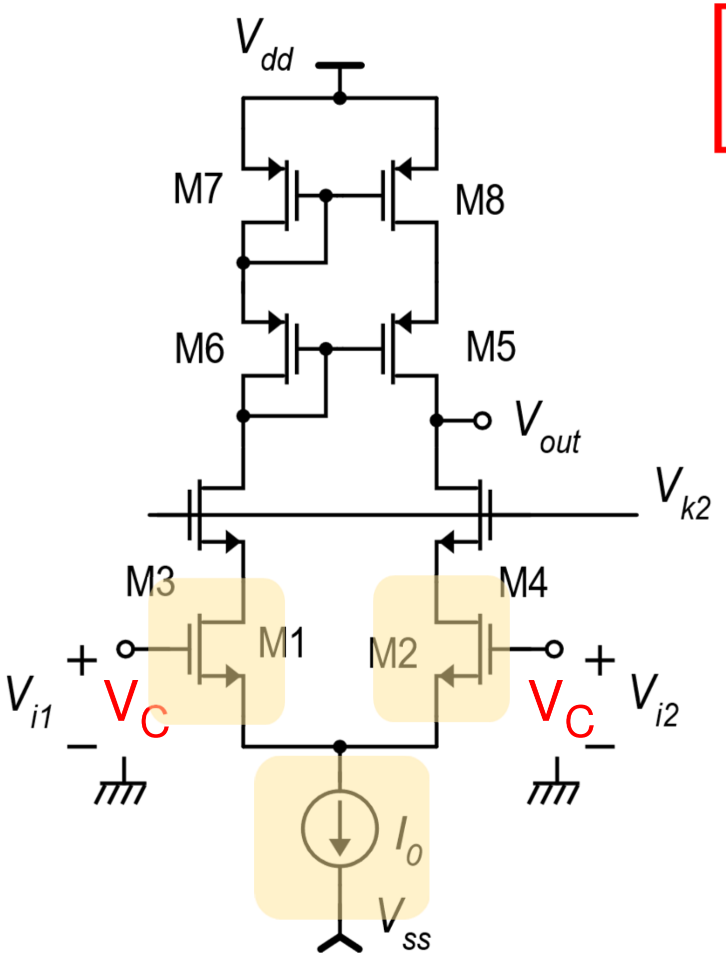
$$V_{out} - V_{k2} + V_{GS4} \geq V_{DSAT4}$$

$$\min(V_{out}) = V_{k2} - V_{GS4} + V_{DSAT4}$$

In strong inversion: $\min(V_{out}) = V_{k2} - V_{t4}$

For an approximation of min(V_{out}) in weak inversion just add 100 mV

Input common mode range



$$\min(V_{iC}) = V_{SS} + V_{MIN-tail} + V_{GS1}$$

$$V_{DS1} = V_{D1} - V_{S1} \geq V_{DSAT1}$$

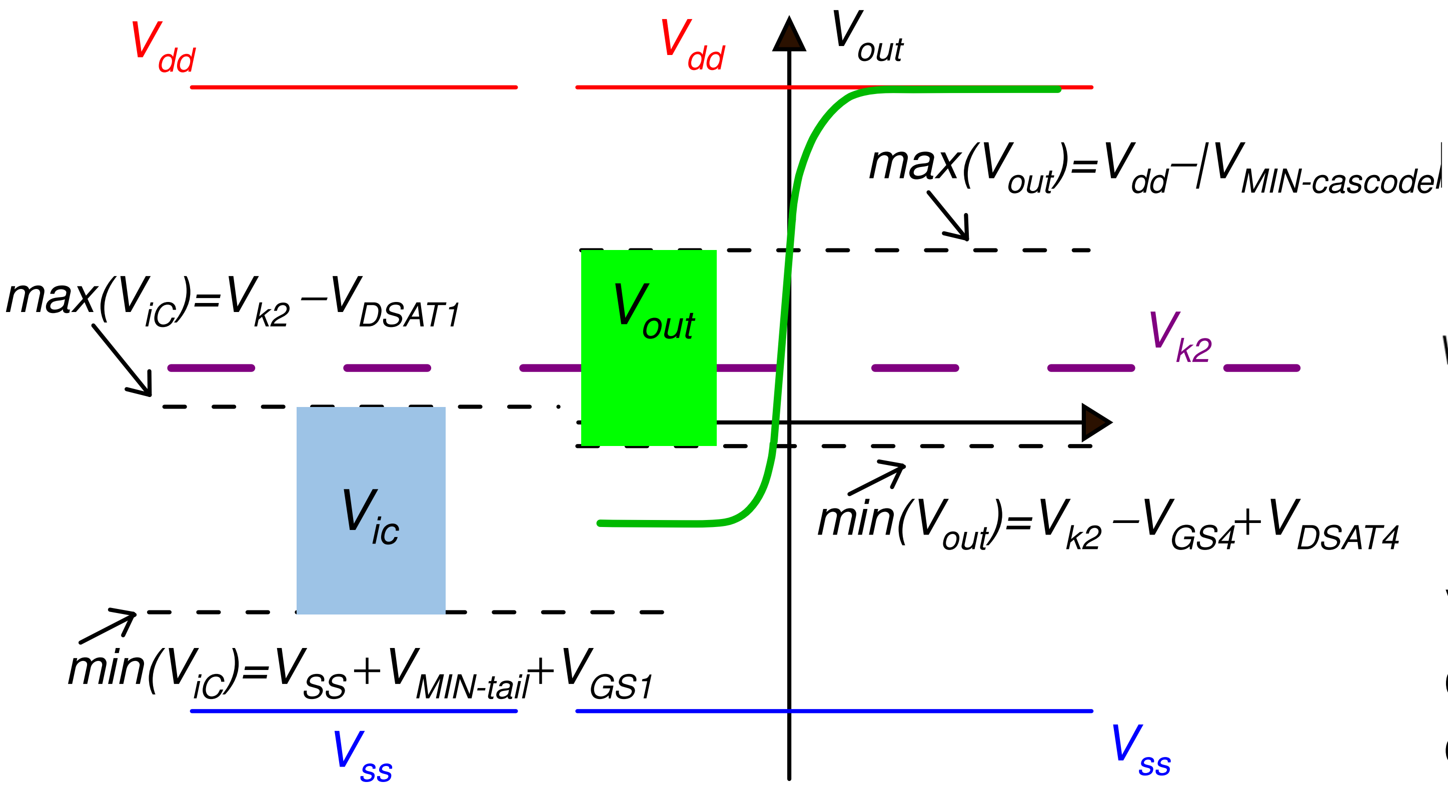
$$\begin{cases} V_{D1} = V_{k2} - V_{GS3} \\ V_{S1} = V_{iC} - V_{GS1} \end{cases}$$

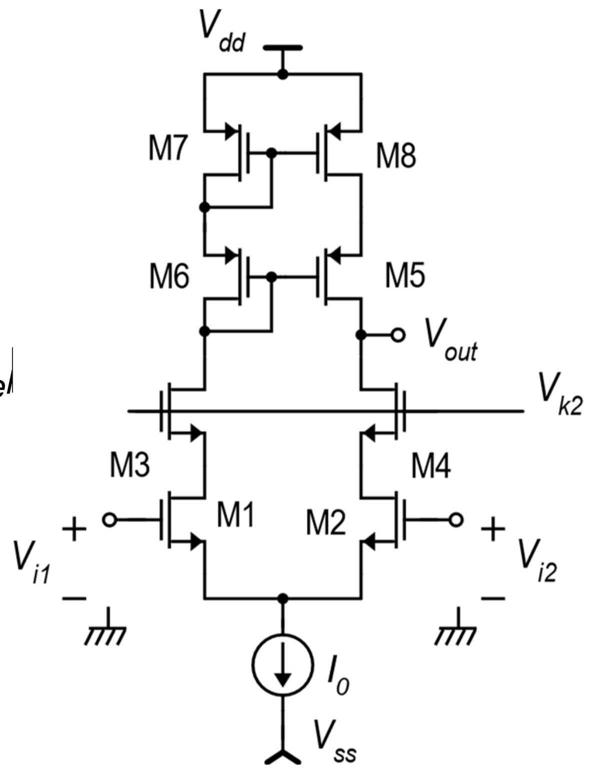
$$V_{k2} - V_{GS3} - V_{iC} + V_{GS1} \geq V_{DSAT1}$$

$$\max(V_{iC}) = V_{k2} \underline{- V_{GS3} + V_{GS1}} - V_{DSAT1}$$

$$\max(V_{iC}) \cong V_{k2} - V_{DSAT1}$$

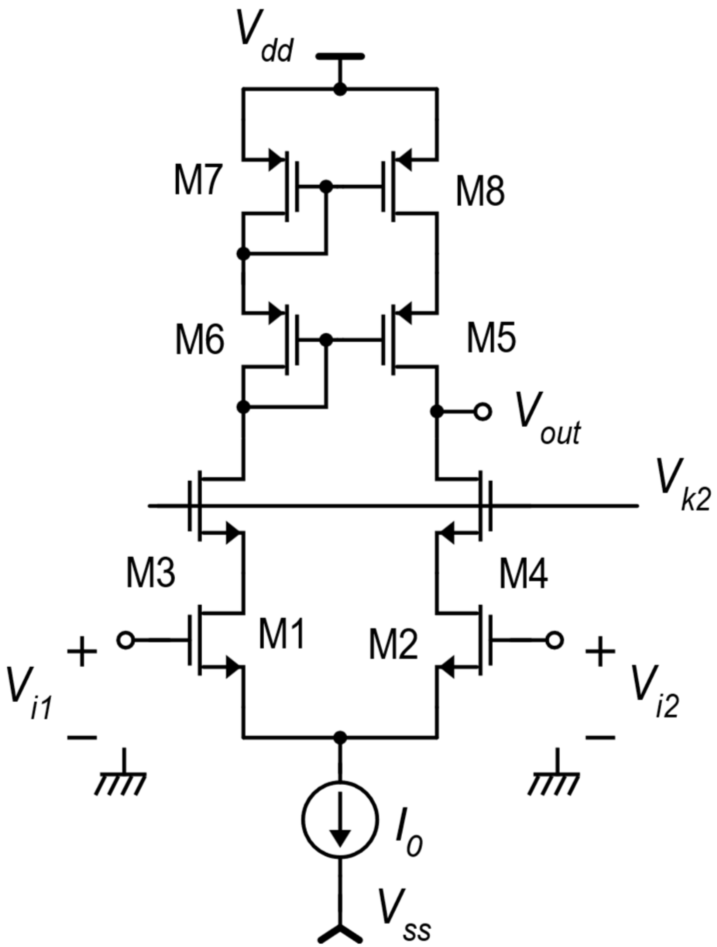
Cascode amplifier: all ranges





V_{k2} determines a trade-off between the input common mode range and the output swing

Adaptive V_{k2}



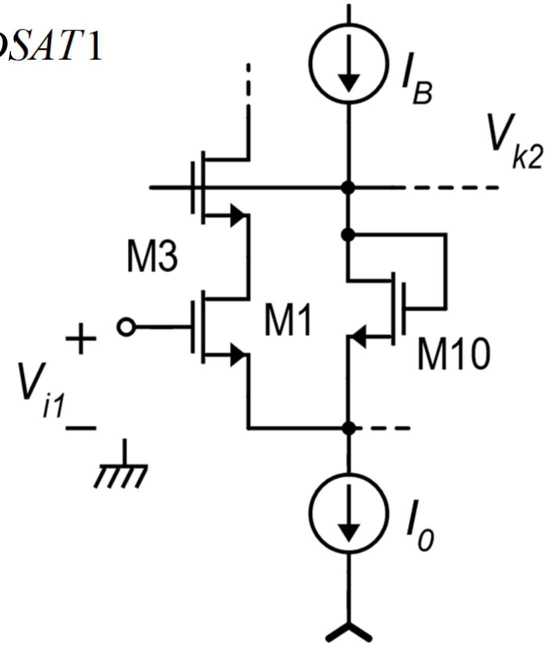
$$V_{k2} - V_{GS3} - V_{iC} + V_{GS1} \geq V_{DSAT1}$$

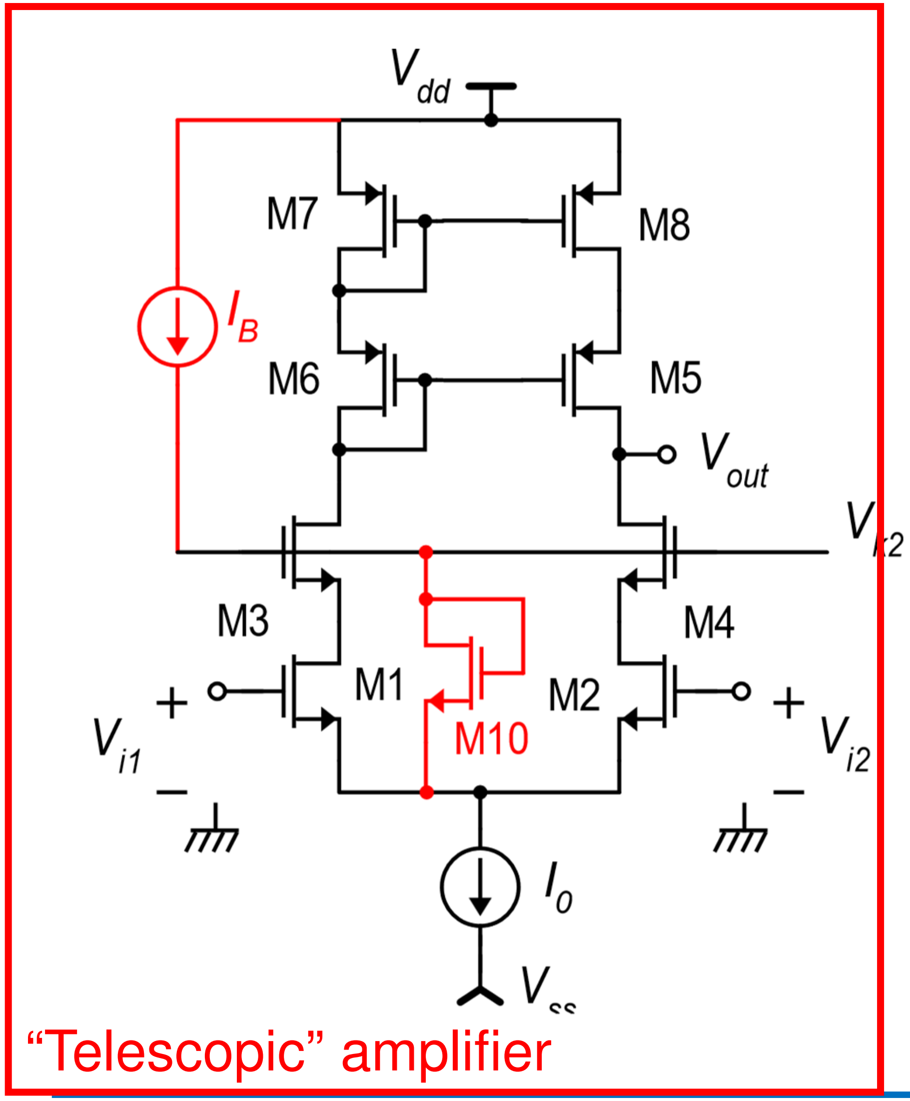
$$V_{k2} \geq \underbrace{V_{iC} - V_{GS1}}_{V_{S1}} + V_{GS3} + V_{DSAT1}$$

$$V_{k2} = V_{S1} + \underbrace{V_{GS3} + V_{DSAT1}}$$

$$V_{k2} = V_{S1} + V_{GS10}$$

$$V_{GS10} = V_{GS3} + V_{DSAT1}$$





Adaptive V_{k2}

Same as in the case of a general cascode structure

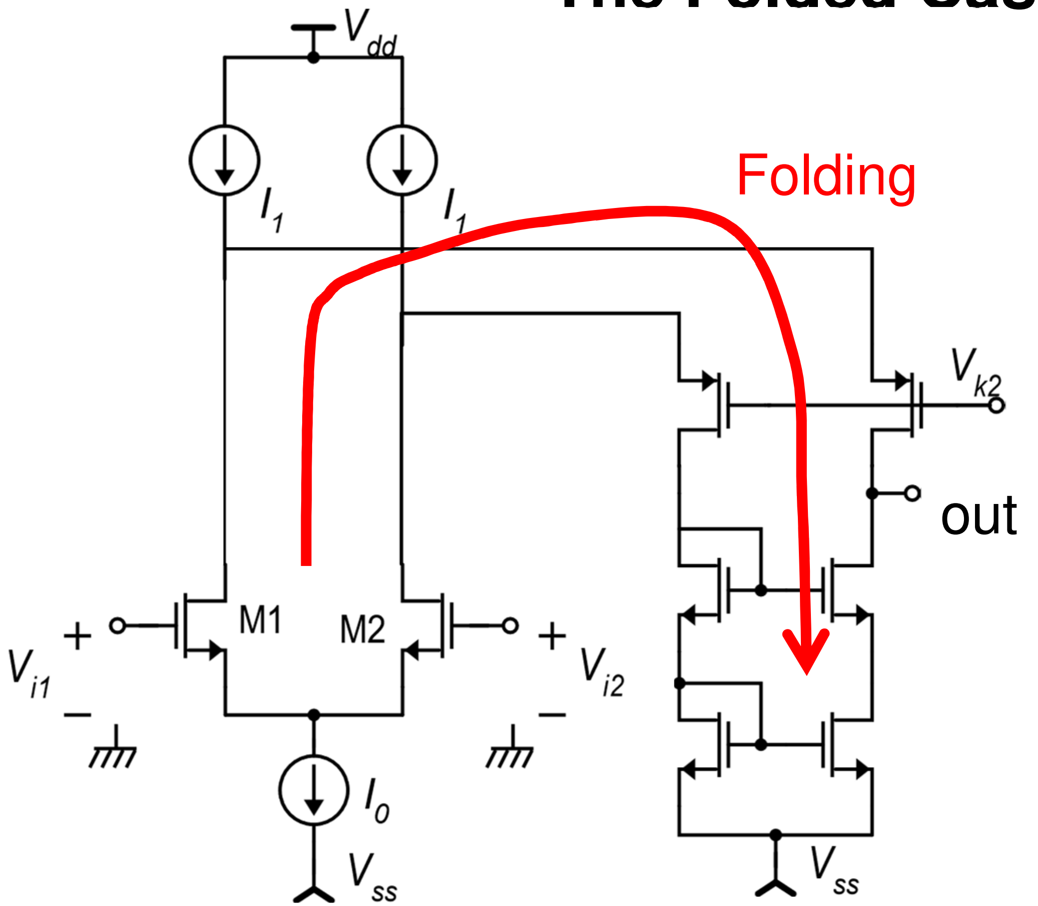
$$V_{GS10} = V_{GS3} + V_{DSAT1}$$

$$\left(V_{GS} - V_t\right)_{10} = m_3 V_{DSAT1} + \left(V_{GS} - V_t\right)_3$$

$$I_{0-eff} = I_0 - I_B$$

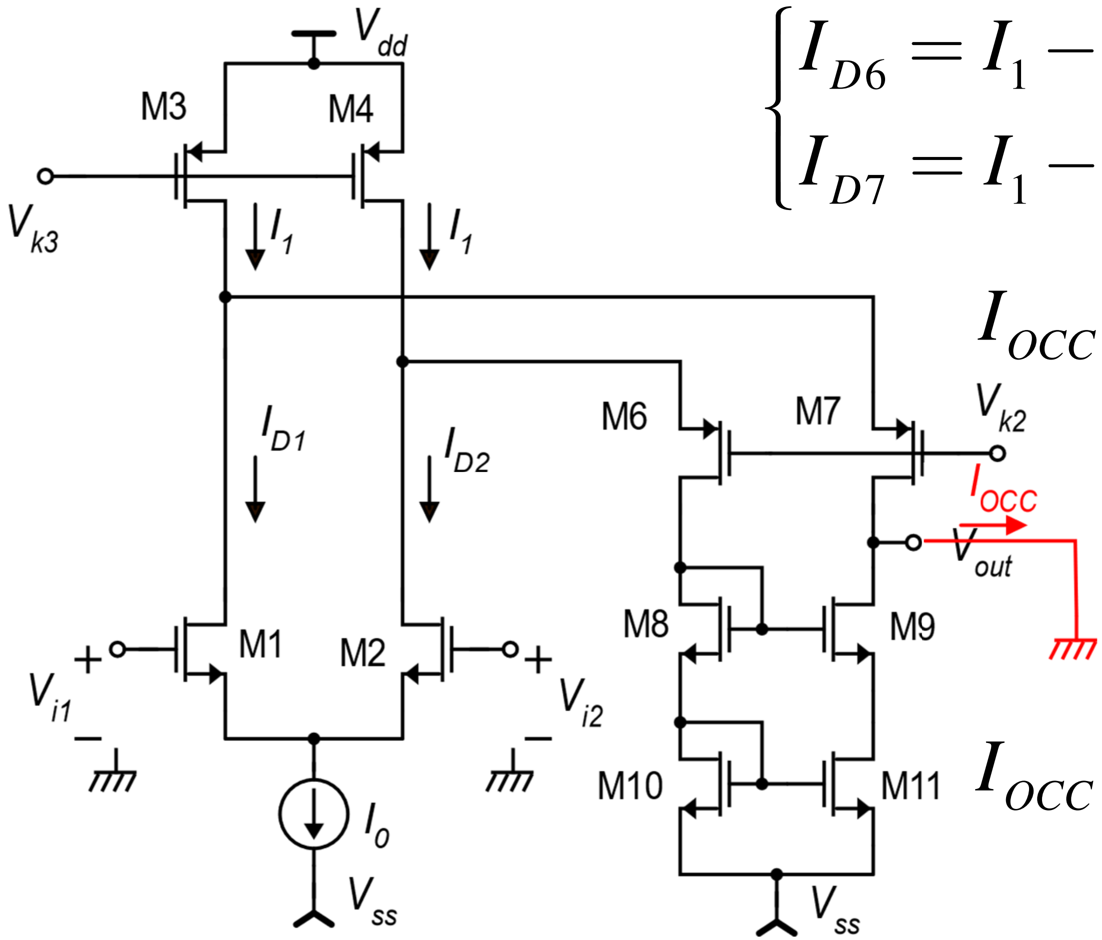
The adaptive V_{k2} does not solve the problem that, as V_{iC} increases, the output swing gets smaller. The advantage is that the amplifier is more flexible and no trade-off on V_{K2} should be made in the design phase.

Removing the interaction between input and output range: **The Folded Cascode**



According to the folding mechanism, the signal (variations) initially travels from one rail to the other and then invert direction and goes back to the initial rail

Folded cascode amplifier: device currents



$$\begin{cases} I_{D6} = I_1 - I_{D2} \\ I_{D7} = I_1 - I_{D1} \end{cases}$$

Condition:

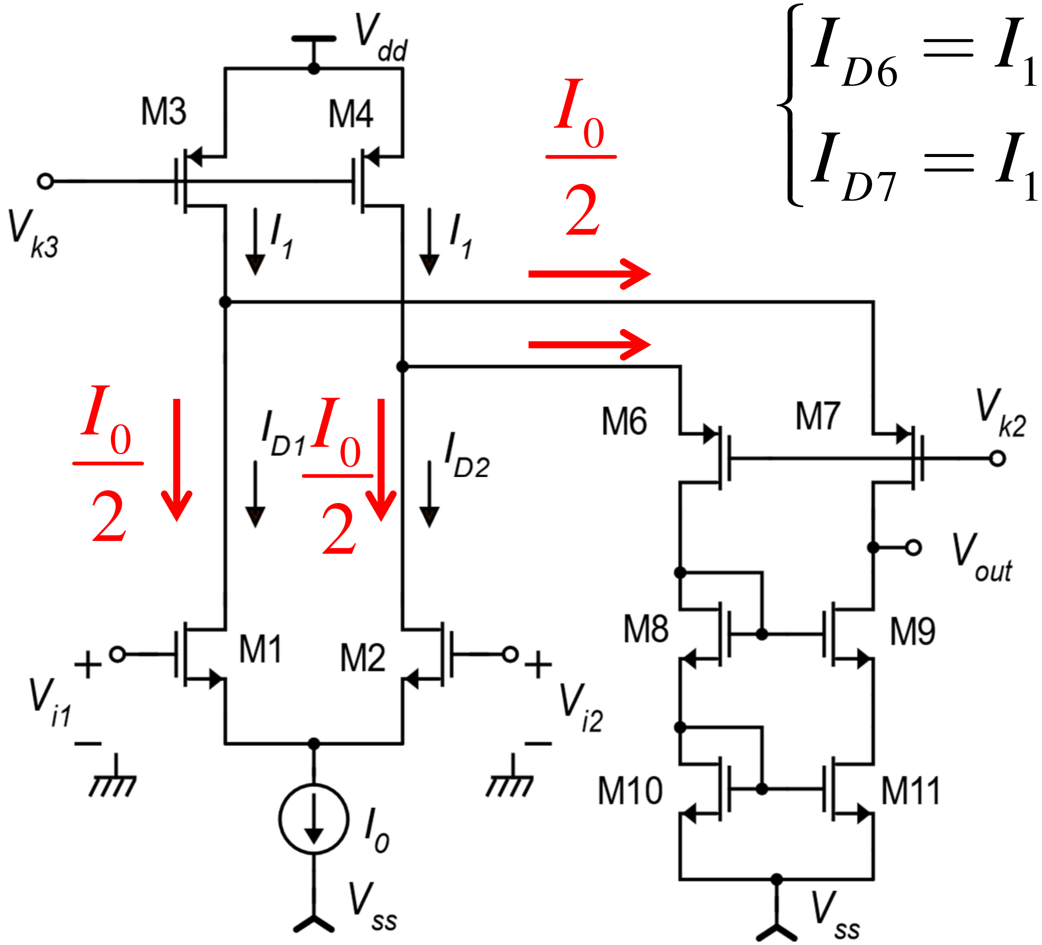
$$\begin{cases} I_{D6} \geq 0 \\ I_{D7} \geq 0 \end{cases}$$

$$I_{OCC} = I_{D7} - I_{D9} \cong I_{D7} - I_{D6}$$

$$I_{OCC} = \left(I_1 - I_{D1}\right) - \left(I_1 - I_{D2}\right)$$

$$I_{OCC} = -\left(I_{D1} - I_{D2}\right) \cong -g_{m1} v_d$$

Folded cascode: setting the correct I_1 value



$$\begin{cases} I_{D6} = I_1 - I_{D2} \geq 0 \\ I_{D7} = I_1 - I_{D1} \geq 0 \end{cases}$$

Quiescent point:

$$I_{D1} = I_{D2} = \frac{I_0}{2}$$

$$I_1 > \frac{I_0}{2}$$

With a large input signal ($|V_{id}| > V_{DMAX}$):

$$V_{id} > V_{DMAX} : I_{D1} = I_0$$

$$V_{id} < -V_{DMAX} : I_{D2} = I_0$$

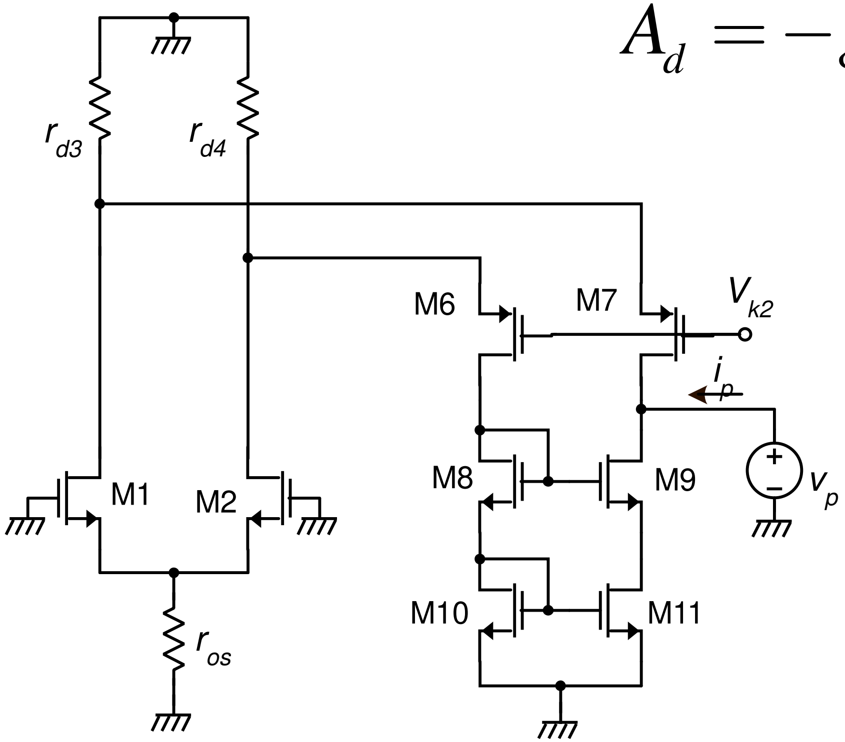
$$I_1 \geq I_0 \qquad \text{usually} : I_1 = I_0$$

Folded cascode: differential mode gain

$$A_d = G_m R_{out}$$

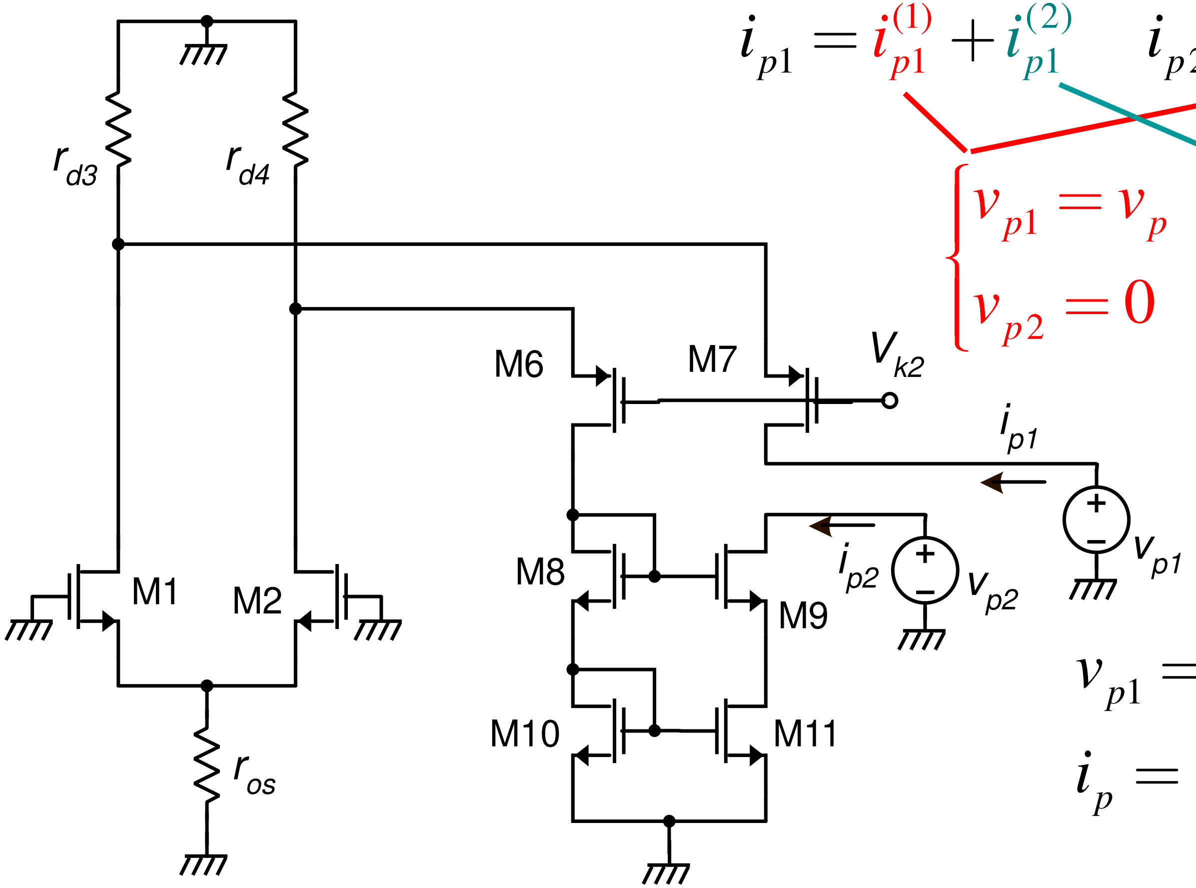
$$I_{OCC} \cong -g_{m1} v_d \Rightarrow G_m = -g_{m1}$$

$$A_d = -g_{m1} R_{out}$$



$$R_{out} = \frac{v_p}{i_p}$$

Folded cascode: output resistance (2)



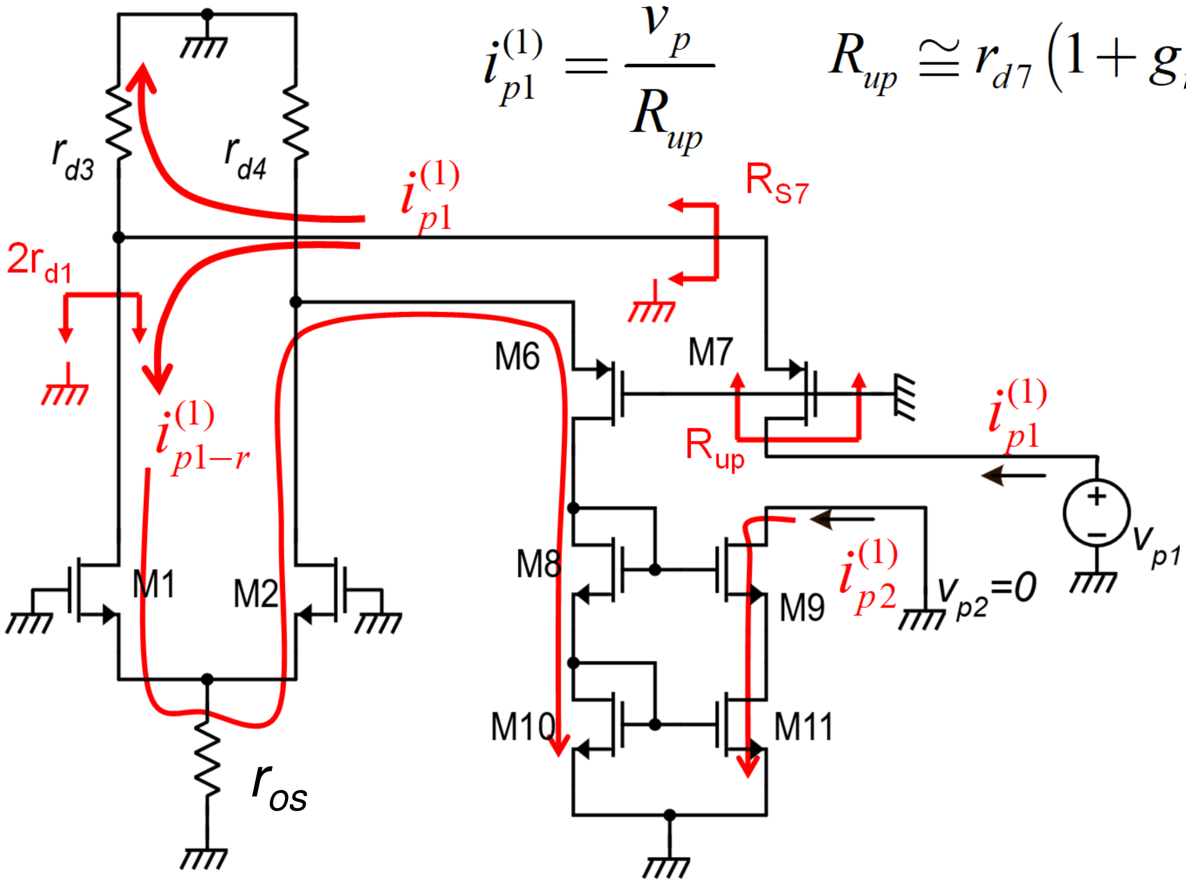
$$i_{p1} = i_{p1}^{(1)} + i_{p1}^{(2)} \qquad i_{p2} = i_{p2}^{(1)} + i_{p2}^{(2)}$$

$$\begin{cases} v_{p1} = v_p \\ v_{p2} = 0 \end{cases} \qquad \begin{cases} v_{p1} = 0 \\ v_{p2} = v_p \end{cases}$$

$$v_{p1} = v_{p2} = v_p$$

$$i_p = i_{p1} + i_{p2}$$

Folded cascode: output resistance (2)



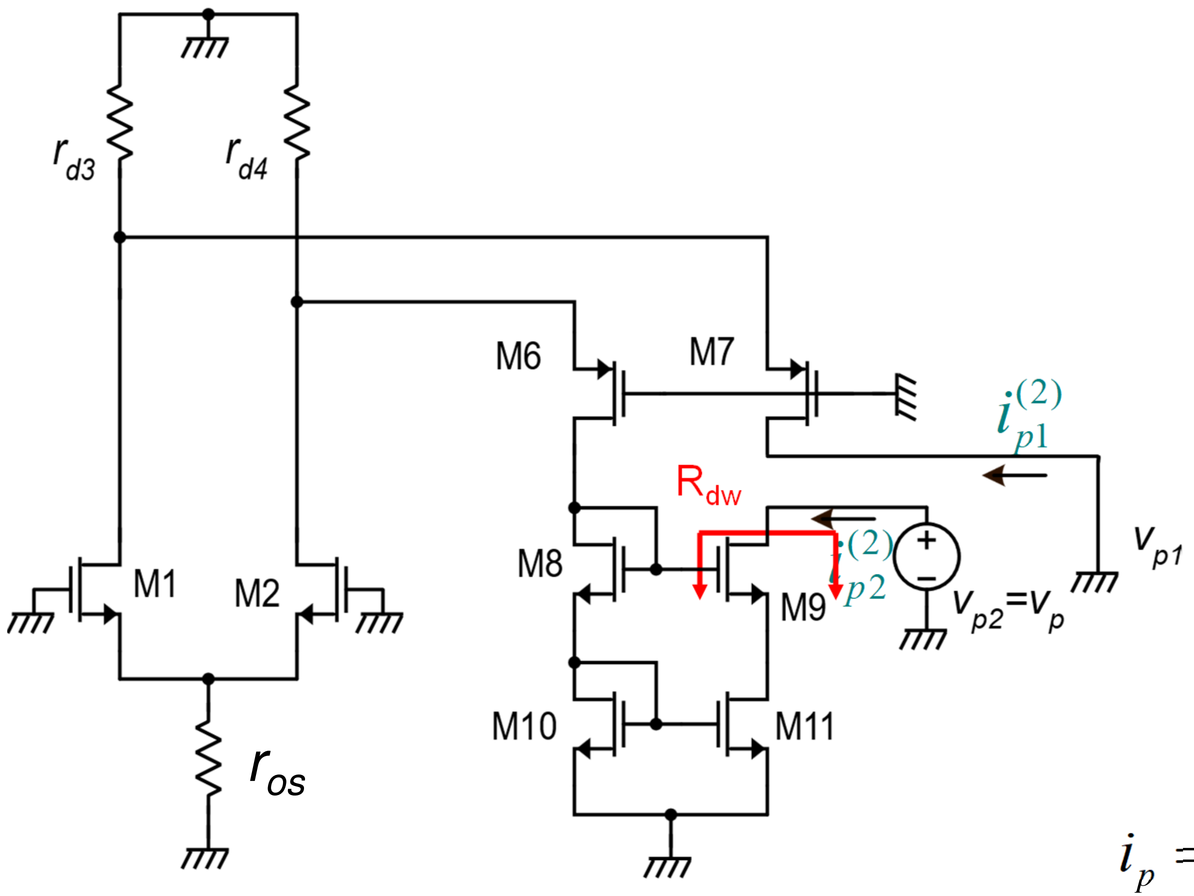
$$i_{p1}^{(1)} = \frac{v_p}{R_{up}} \qquad R_{up} \cong r_{d7}\left(1 + g_{m7}R_{S7}\right) \qquad R_{S7} = r_{d3} // 2r_{d1}$$

$$R_{up} \cong r_{d7}g_{m7}\left(r_{d3} // 2r_{d1}\right)$$

$$i_{p1-r}^{(1)} = i_{p1}^{(1)} \frac{r_{d3}}{r_{d3} + 2r_{d1}}$$

$$i_{p2}^{(1)} = i_{p1-r}^{(1)} = i_{p1}^{(1)} \frac{r_{d3}}{r_{d3} + 2r_{d1}}$$

Folded cascode: output resistance (2)



$$R_{dw} \cong r_{d9} g_{m9} r_{d11}$$

$$i_{p2}^{(2)} = \frac{v_p}{R_{dw}}$$

$$i_{p1}^{(2)} = 0$$

$$i_{p1}^{(1)} = \frac{v_p}{R_{up}}$$

$$i_{p2}^{(1)} = i_{p1}^{(1)} \frac{r_{d3}}{r_{d3} + 2r_{d1}}$$

$$i_p = \frac{v_p}{R_{up}} \left(1 + \frac{r_{d3}}{r_{d3} + 2r_{d1}} \right) + \frac{v_p}{R_{dw}}$$

Folded cascode: output resistance (3)

$$i_p = v_p\left(\frac{1}{R_{up}}\left(1+\frac{r_{d3}}{r_{d3}+2r_{d1}}\right)+\frac{1}{R_{dw}}\right)$$

$$R_{out} = \left(\frac{1}{R_{up}}\left(1+\frac{r_{d3}}{r_{d3}+2r_{d2}}\right)+\frac{1}{R_{dw}}\right)^{-1}$$

$$R_{out} = \left(\frac{1}{\dfrac{R_{up}}{\left(1+\dfrac{r_{d3}}{r_{d3}+2r_{d1}}\right)}}+\frac{1}{R_{dw}}\right)^{-1}$$

$$R_{out} = R_{dw} // R_{up-r}$$

$$R_{dw} = r_{d9} g_{m9} r_{d11} \qquad R_{up-r} = \frac{r_{d7} g_{m7} \left(r_{d3} // 2r_{d1}\right)}{\left(1+\dfrac{r_{d3}}{r_{d3}+2r_{d1}}\right)}$$

If $r_{d2}=r_{d3}=r_{d7}=r_{d9}=r_{d11}=r_d$, $g_{m7}=g_{m9}=g_m$

$r_{d3} // 2r_{d1} = \frac{2}{3} r_d$

$1+\frac{r_{d3}}{r_{d3}+2r_{d1}} = \frac{4}{3}$

$$R_{dw} = r_d\left(g_m r_d\right)$$

$$R_{up-r} = \frac{r_d\left(g_m r_d\right)}{2}$$

$$R_{out} = \frac{r_d\left(g_m r_d\right)}{3}$$

Folded cascode: differential mode gain

$$A_d = -g_{m1} R_{out}$$

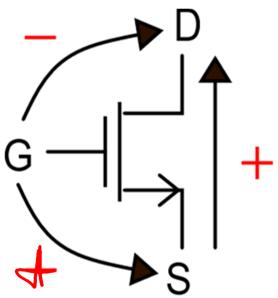
If $r_{d2}=r_{d3}=r_{d7}=r_{d9}=r_{d11}=r_d$
$g_{m7}=g_{m9}=g_{m1}=g_m$

$$A_d = -g_m \frac{r_d\left(g_m r_d\right)}{3} = -\frac{\left(g_m r_d\right)^2}{3}$$

Compare with the "Telescopic" amplifier $\quad A_d = \frac{\left(g_m r_d\right)^2}{2}$

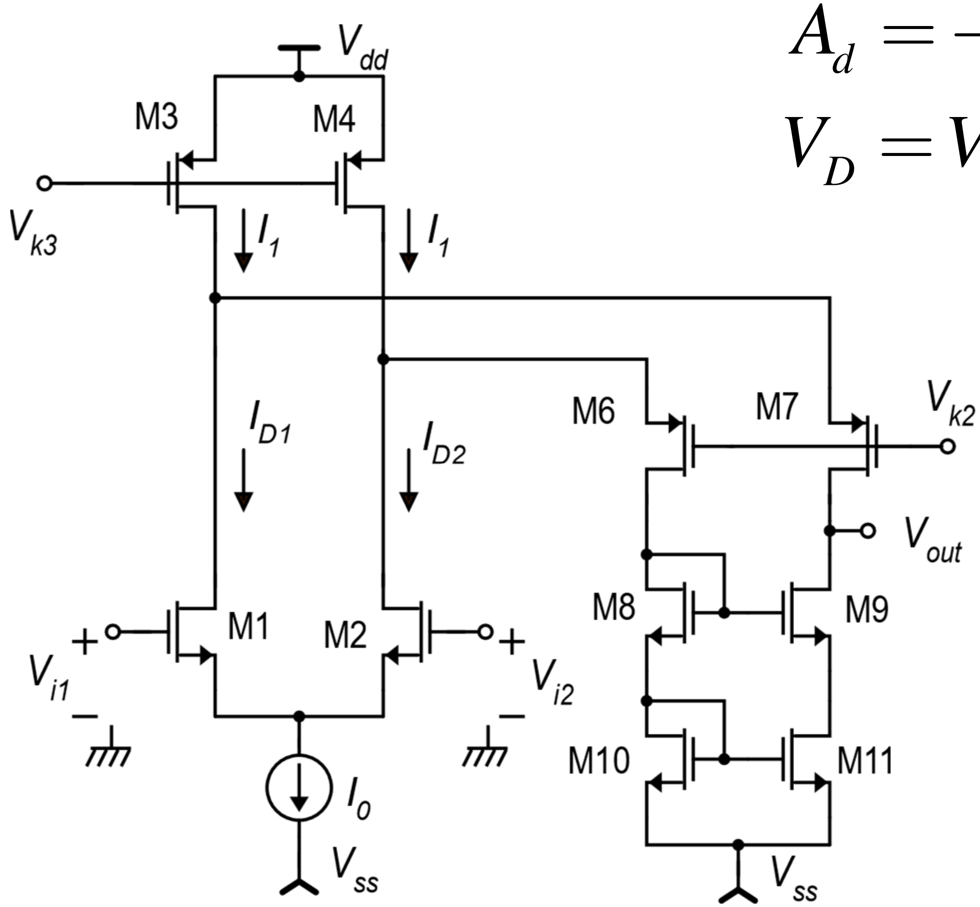
… and with the simple amplifier with mirror load (non-cascode) $\quad A_d = \frac{\left(g_m r_d\right)}{2}$

Simple method to find if a terminal is inverting / non-inverting



$$A_d = -g_{m1} R_{out}$$

$$V_D = V_{i1} - V_{i2}$$

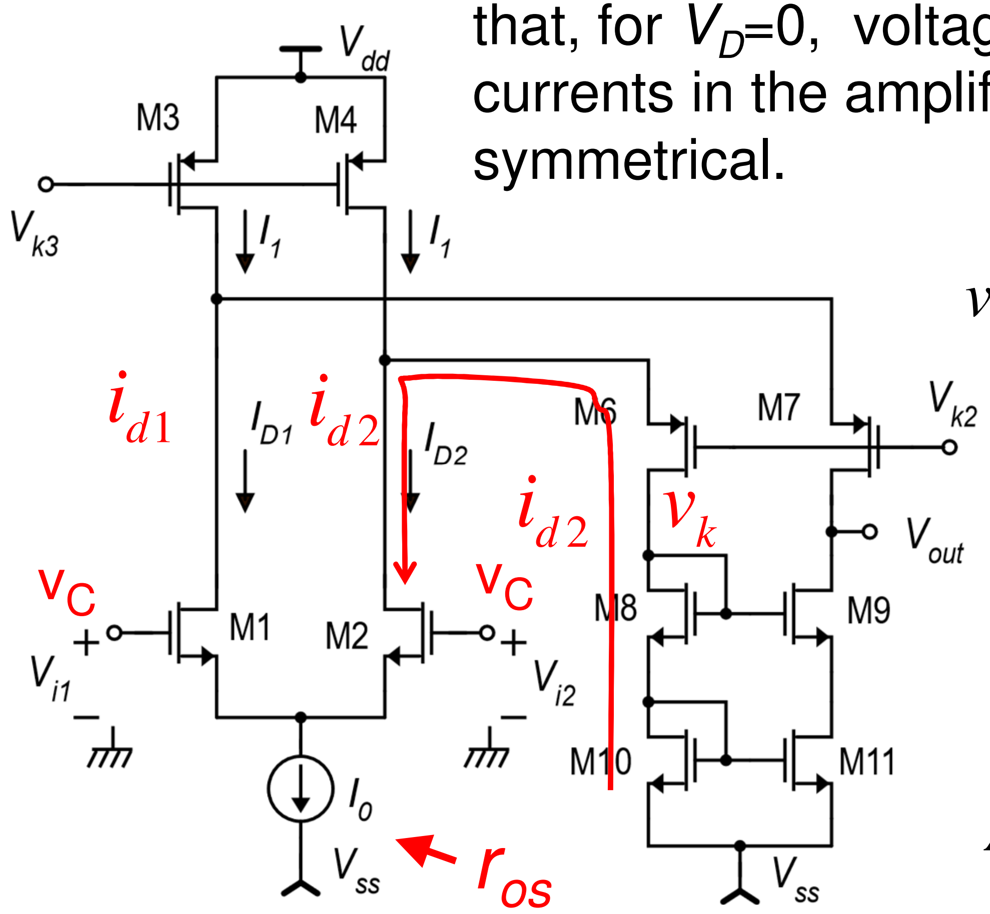


Signal paths:

1. From G to D: inversion
2. From G to S: no inversion
3. From S to D: no inversion

Ac, CMRR

It is possible to demonstrate that, for V_D=0, voltage and currents in the amplifiers are symmetrical.



Then: $\begin{cases} i_{d1} = i_{d2} \cong \dfrac{v_c}{2r_{os}} \\ v_{out} = v_k \end{cases}$

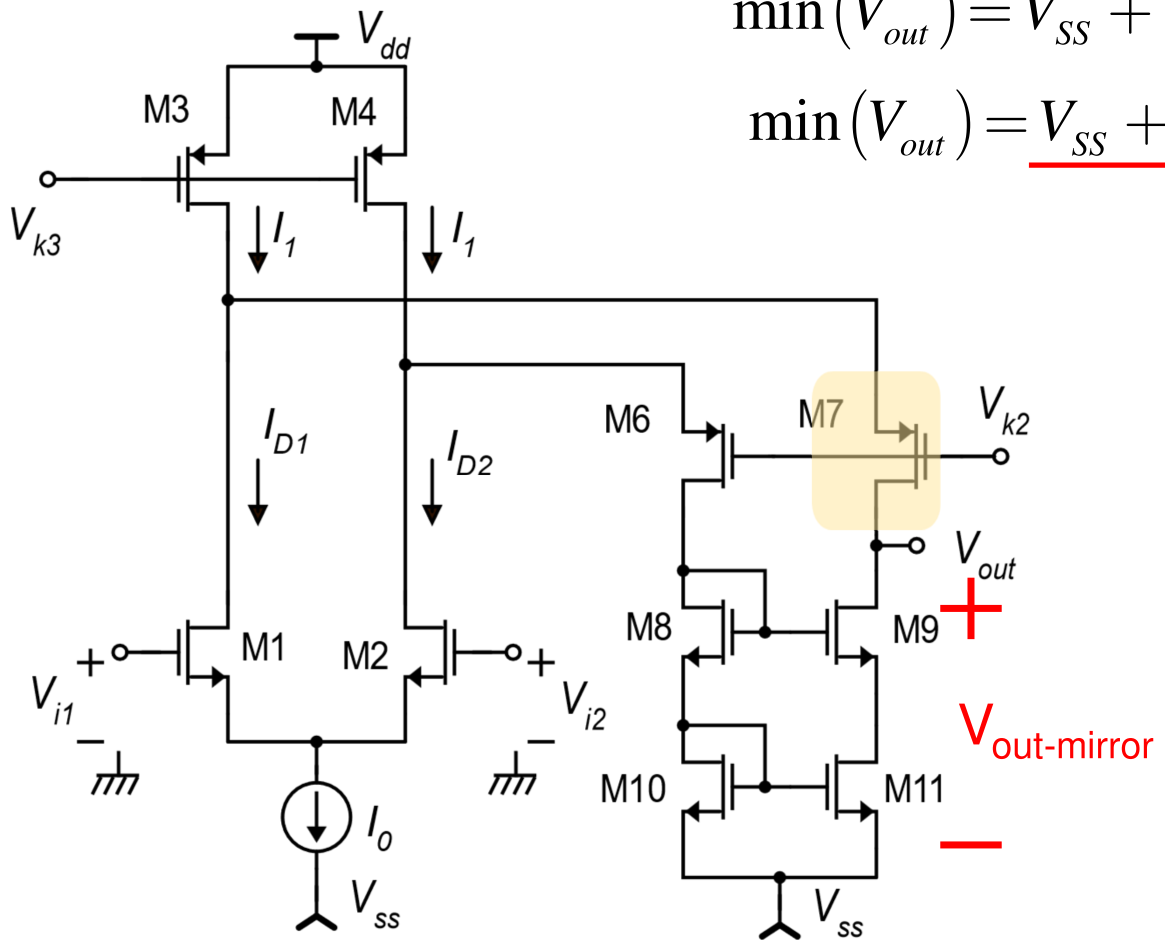
$$v_{out} = v_k = -i_{d2}\left(\frac{1}{g_{m8}} + \frac{1}{g_{m10}}\right)$$

$$v_{out} = -\frac{v_c}{2r_{os}}\left(\frac{1}{g_{m8}} + \frac{1}{g_{m10}}\right) = -\frac{v_c}{g_m r_{os}}$$

for $g_{m8} = g_{m10} = g_m$

$$A_C = -\frac{1}{g_m r_{os}} \qquad CMRR \approx \frac{(g_m r_d)^2}{3} g_m r_{os}$$

Folded cascode: output range



$$\min(V_{out}) = V_{SS} + V_{MIN-cascode}$$

Lower limit

$$\min(V_{out}) = \underline{V_{SS} + V_{GS11} + V_{DSAT9}}$$

Upper limit

$$|V_{DS7}| = V_{k2} + |V_{GS7}| - V_{out} \geq |V_{DSAT7}|$$

$$V_{k2} + |V_{GS7}| - |V_{DSAT7}| \geq V_{out}$$

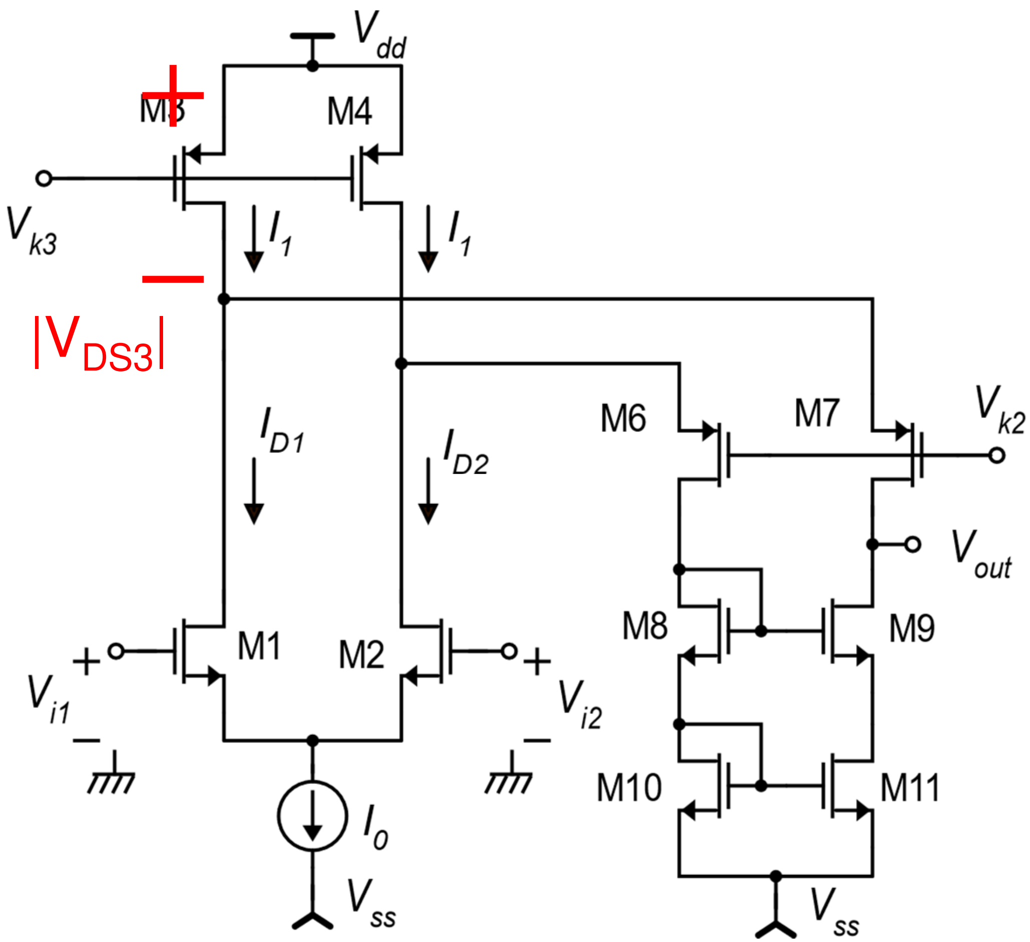
$$\max(V_{out}) = \underline{V_{k2} + |V_{GS7}| - |V_{DSAT7}|}$$

In strong inversion:

$$|V_{DSAT7}| = |V_{GS7}| - |V_{t7}|$$

$$\max(V_{out}) = V_{k2} + |V_{t7}|$$

Maximum V_{k2}



$$\max(V_{out}) = V_{k2} + |V_{GS7}| - |V_{DSAT7}|$$

$$V_{D3} = V_{D1} = V_{k2} + |V_{GS7}|$$

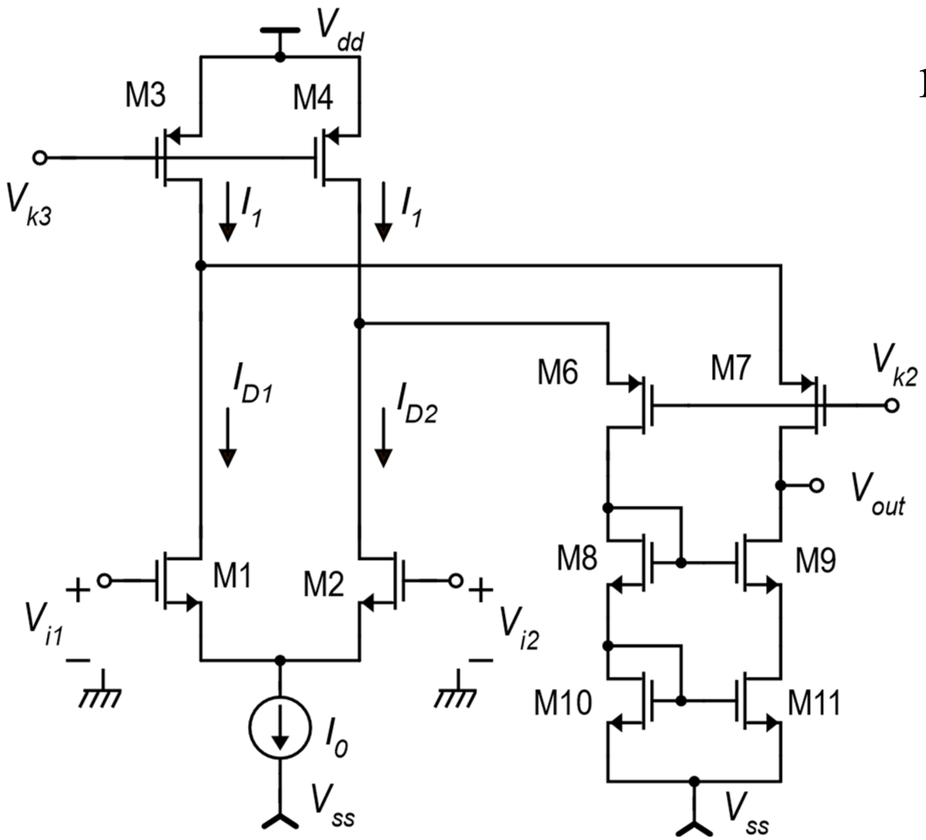
V_{k2} sets the voltage of M1-M3 and M2-M4 drains

$$|V_{DS3}| = V_{dd} - V_{D3} = V_{dd} - V_{k2} - |V_{GS7}| \geq |V_{DSAT3}|$$

$$\max(V_{k2}) = V_{dd} - |V_{DSAT3}| - |V_{GS7}|$$

$$\max(V_{out}) = V_{dd} - |V_{DSAT3}| - |V_{DSAT7}|$$

Input common mode range



$$\min(V_{iC}) = V_{SS} + V_{MIN-tail} + V_{GS1}$$

$$V_{D3} = V_{D1} = V_{k2} + |V_{GS7}|$$

M1 (M2) has the drain at a fixed voltage. If the gate voltage increases, M1 (M2) will eventually leave saturation

$$V_{DS1} = V_{D1} - V_{S1} =$$

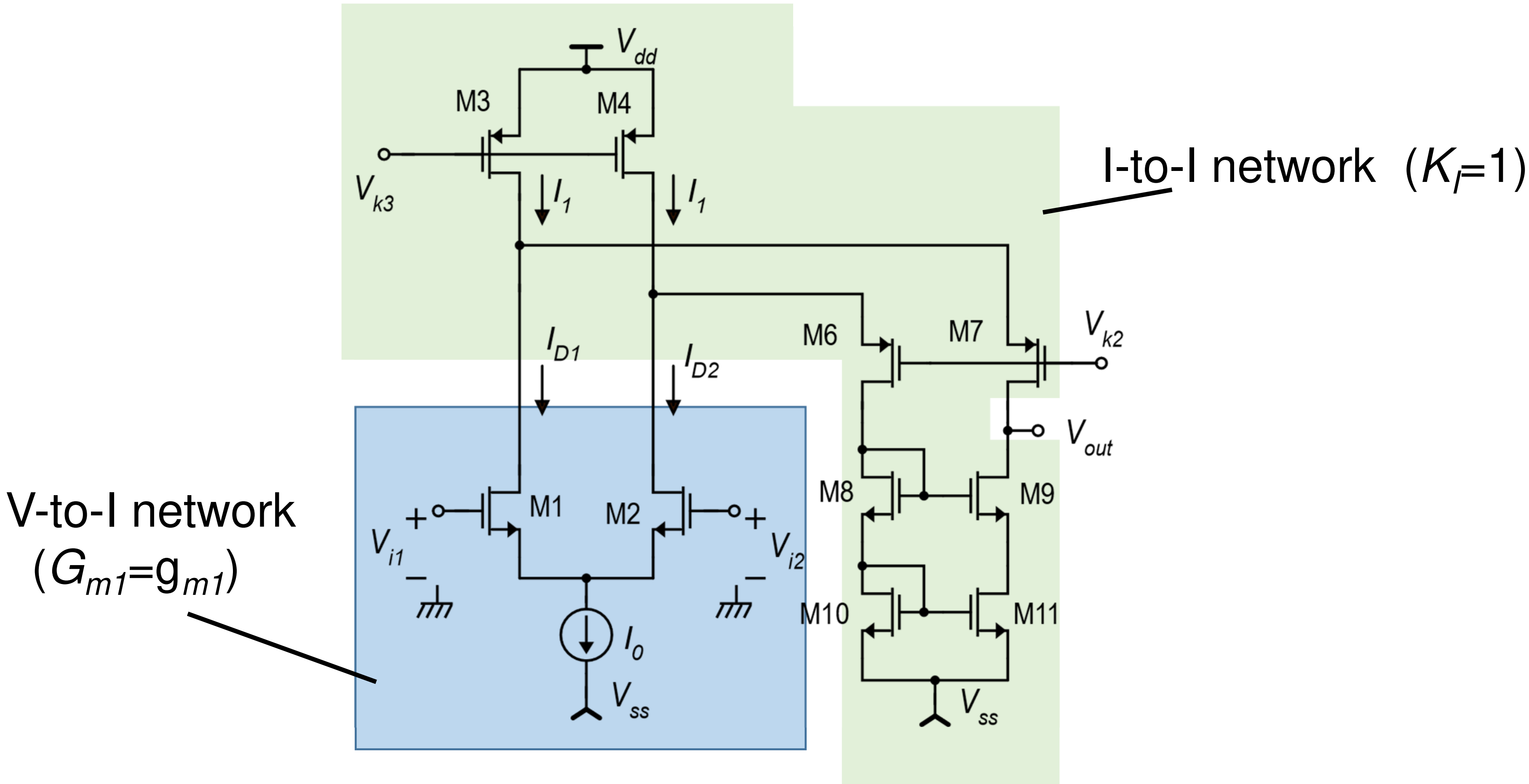
$$= V_{k2} + |V_{GS7}| - (V_C - V_{GS1}) \geq V_{DSAT1}$$

$$\max(V_C) = V_{k2} + |V_{GS7}| + V_{GS1} - V_{DSAT1}$$

$$\max(V_{k2}) = V_{dd} - |V_{DSAT3}| - |V_{GS7}|$$

$$\max(V_C) = V_{dd} - |V_{DSAT3}| + V_{GS1} - V_{DSAT1}$$

The folded cascode as a single stage amplifier



Folded cascode: summary of properties

DC Gain: Slightly smaller than the telescopic amplifier (non-folded cascode) gain. May reach several thousands or even 10^4 (80 dB) with long mosfets. Larger than the gain of the cascade of two common source stages.

Output swing:

$$\max(V_{out}) = V_{dd} - |V_{DSAT3}| - |V_{DSAT7}|$$

$$\min(V_{out}) = V_{SS} + V_{GS11} + V_{DSAT9}$$

Input CM range:

$$\min(V_{iC}) = V_{SS} + V_{MIN-tail} + V_{GS1}$$

$$\max(V_C) = V_{dd} - |V_{DSAT3}| + V_{GS1} - V_{DSAT1}$$

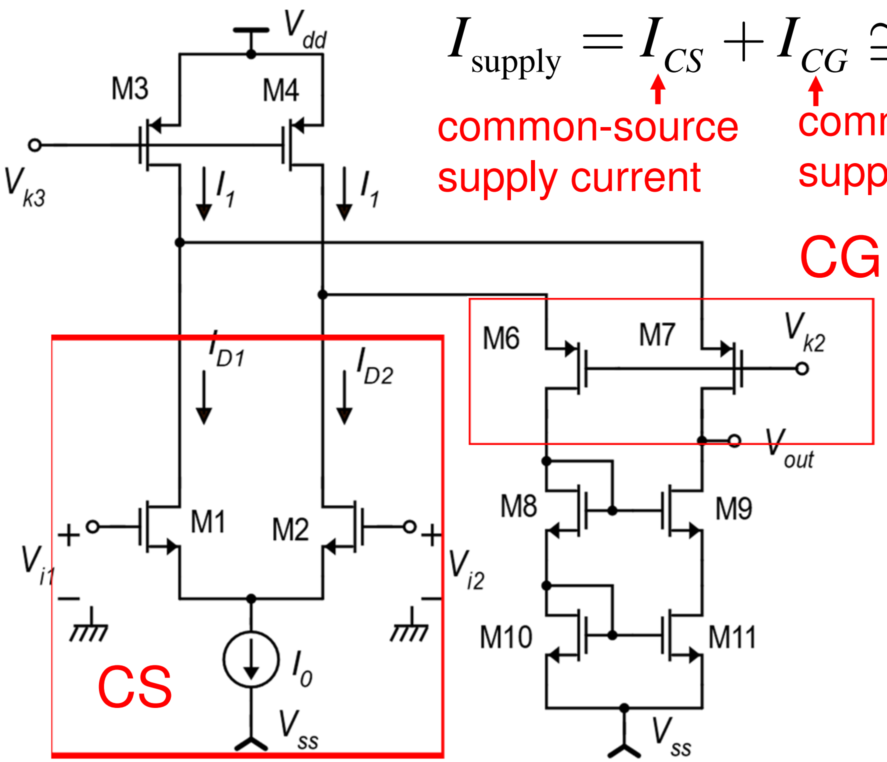
The only true advantage of the telescopic amplifier

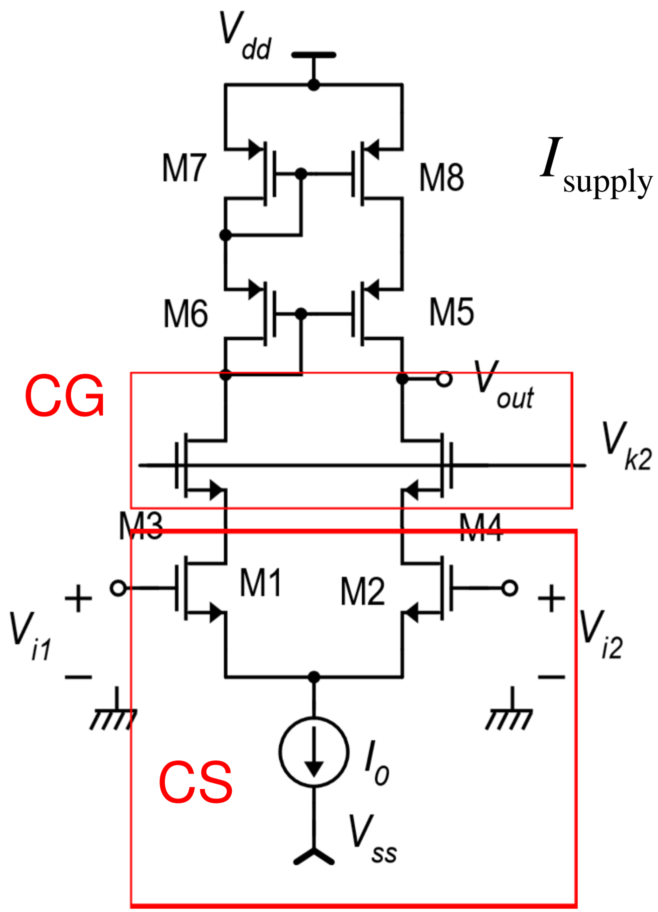
Current consumption (I_{supply})

$$I_{\text{supply}} = I_{CS} + I_{CG} \cong 2I_0$$

common-source supply current

common-gate supply current





$$I_{\text{supply}} = I_{CS} \cong I_0$$

Current re-use

Example of BJT Op-Amp with a Folded cascode input stage

THS4031-EP
THS4032-EP

TEXAS INSTRUMENTS

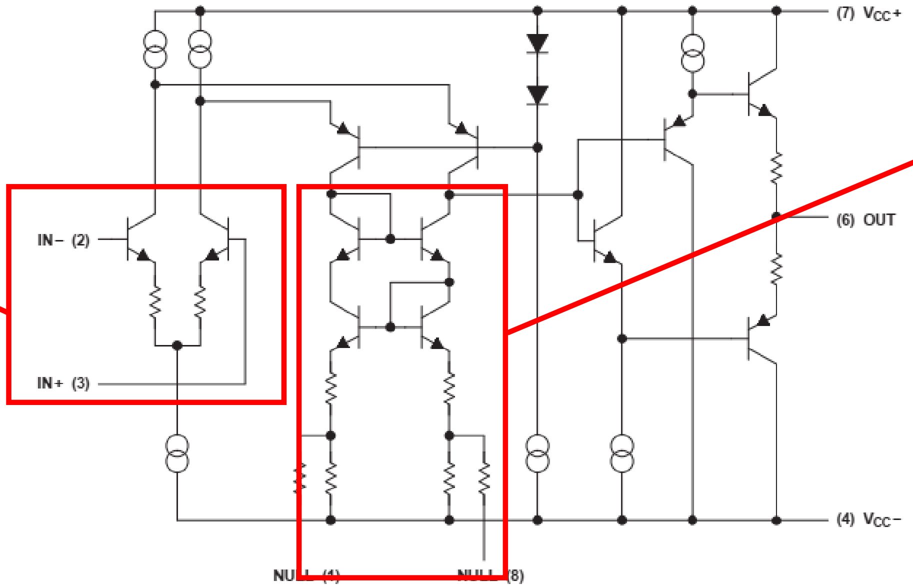
SLOS610–NOVEMBER 2008 www.ti.com

APPLICATION INFORMATION

THEORY OF OPERATION

The THS403x is a high-speed operational amplifier configured in a voltage feedback architecture. It is built using a 30-V, dielectrically isolated, complementary bipolar process with NPN and PNP transistors possessing f_Ts of several GHz. This results in an exceptionally high-performance amplifier that has wide bandwidth, high slew rate, fast settling time, and low distortion. A simplified schematic is shown in Figure 51.

Emitter-degenerated input pair (improves input differential range, with benefits in terms of Slew-Rate



Wilson current mirror with emitter degeneration.

Figure 51. THS4031 Simplified Schematic